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AERONAUTICAL RESEARCH LABS MELBOURNE (AUSTRALIA)  
IMPACT TESTS ON CRASH HELMETS FOR MOTOR CYCLISTS, (U)  
APR 78 N D HEARN, S R SARRAILHE  
ARL-STRUC NOTE-445

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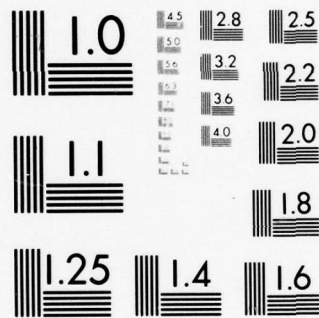
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AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

STRUCTURES NOTE 445

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### IMPACT TESTS ON CRASH HELMETS FOR MOTOR CYCLISTS

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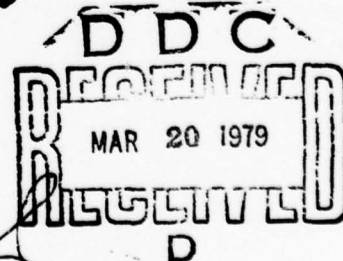
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N. D. HEARN and S. R. SARRAILHE

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AR-001-263

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## 1. INTRODUCTION

The function of a crash helmet is to mitigate the effect of impact by spreading the load over the skull, and cushioning the blow, so that the impact acceleration, or force on the head, is reduced to a tolerable value. As no practical helmet could attenuate all foreseeable impacts to a safe level, the test criteria must be chosen to ensure that the protection provided is as good as is practicable at the time, using the most suitable available materials and design principles.

The construction and materials of protective headgear for motor-cyclists have improved since the introduction of the first helmet standard<sup>1</sup> in 1953, and the specifications have been revised to ensure that these improvements are incorporated in all production helmets complying with the standard. (For example, the penetration test in Z90.1 of 1971<sup>2</sup> is three times as severe as in the 1966 version of the standard.<sup>3</sup>)

The standards have also been revised to improve the methods of testing.

It follows that the development of the standard, to ensure all helmets provide good protection, and development of the helmets, must be based on the performance of good contemporary products. To provide this data and to provide supporting evidence for the adoption of an up-to-date Australian standard several samples of seven types (or brands) of typical helmets, intended for use by motor cyclists, were subjected to a series of tests.

The tests were carried out in accordance with the procedures described in the American National Standards Institute Specification Z90.1-1971.<sup>2</sup> This standard was the basis for the US Federal Motor Vehicle Safety Standard,<sup>4</sup> and the early results of these tests led to its adoption as the current Australian standard.<sup>5</sup>

The helmets were tested at room temperatures and were not subjected to hot, cold or wet conditioning in the laboratory although some samples were exposed to the weather before testing.

All helmets carried labels claiming compliance with recognized standards, but some of these were less severe than ANSI Z90.1-1971.

It might be thought that the performance could be predicted by reference to the relevant standard, but previous experience with helmet tests,<sup>6</sup> suggested that the performance of some helmets may be much better than demanded by the specification; whereas an American survey<sup>7</sup> in 1972 stated—

“Almost 90 per cent of the motorcycle helmets tested for the Government failed to meet the performance requirements set by industry specifications.

“The Department's National Highway Traffic Safety Administration (NHTSA), said that 74 tests of 54 different model helmets showed that only eight complied with the standard set by the industry's American National Standards Institute. The Safety Administration said the test results are not regarded as conclusive, but offer an initial attempt at comparison of the performance of safety helmets and illustrate the need for further examination.”

The current tests were to show whether this high failure rate also applied in Australia, and if so, to provide an explanation. Possible explanations could include:

1. Requirements which could not be achieved by typical production helmets; or
2. Ambiguities in the standard which could allow one tester to show compliance whilst another tester could show a deficiency in performance.

It was thought that one example of this could be in the choice of test sites on the helmet, because a test near the crown is likely to produce a more favourable result than one near the edge.

The helmet should provide protection when struck at any position and a typical specification<sup>2</sup> in defining the extent of protection states:

“The entire area of the protective headgear above the reference plane shall attenuate impact energy to at least the minimum requirements specified in Section 9.”

The helmet should be tested to prove the performance but clearly this can only be done at a few positions. Specification Z90.1<sup>2</sup> states:

"The impact sites shall be above the reference plane and separated from each other by a distance not less than one-sixth of the maximum circumference of the protective headgear."

Other standards,<sup>3,5</sup> recognising the difficulty of testing on the extreme edge specify a "test line" 25 mm above the reference plane\* at the front of the helmet, but none of the standards referred to specifies a maximum distance from the "test line", so thus the certification testing may be carried out well away from the edge.

Accident data from several sources including an Australian survey (in 1966) indicate that in accidents the impact is most likely to be near the edge as shown in Figure 1; moreover the authors<sup>6</sup> observed that:

"50 per cent of this series of impacts fall in an area where there is no protective padding in the standard helmet."

Fortunately, in modern helmets, the energy absorbing liner extends nearer to the edge, but performance away from the edge still may not be a true indication of performance over the entire area above the reference plane, and in particular the performance in the critical edge region.

The US standards<sup>2,3,4</sup> differ from earlier Australian standards<sup>9</sup> by requiring

"two successive identical impacts (the centres of each paired impacts shall be located not more than  $\frac{1}{4}$  inch (6 mm) apart) in not less than four sites"

and requiring impacts on a hemispherical anvil in addition to impacts on a flat surface. These requirements had not previously been investigated in Australia and the tests were made to determine:

1. the impact accelerations when the helmeted headform was dropped onto flat and hemispherical surfaces;
2. the effect of a second impact at the same point on the helmet;
3. the effect of impact near the edge of the helmet;
4. the effect of the large increase in the severity of the penetration test from the requirements of the 1966 version of standard Z90.1 to the 1971 edition;
5. an indication of the performance of typical helmets in relation to standard specifications;
6. the relative performance of the two common shell materials (fibreglass and polycarbonate);
7. the effect of weathering.

The work was carried out as part of the ARL Crash Safety Program, which is supported by the Department of Transport. The program is concerned primarily with safety in aviation, but many of the criteria for helmets for use in aviation and on the road are similar.

## 2. THE HELMETS

The helmets were purchased in Melbourne in 1973, and were selected after an examination of helmets for sale in several of the larger motorcycle equipment stores. They were considered typical of helmets of current production and claimed compliance with recognised standards. European, American and Japanese manufacturers were represented.

Most of the helmets examined used a moulded polystyrene foam liner for shock absorption, and six of the seven types chosen for testing were of this type. One type (No. 2) was chosen to

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Footnote: Definitions from Reference 2.

\* *Reference Plane.* The standard headform, on which the basic plane is marked, shall be positioned on a flat surface so that the basic plane is parallel to this surface. The reference plane shall be scribed on the helmet after it has been positioned on the test head so that the lowermost part of the leading edge at the front of the helmet is 2.36 inches (60 mm) above the basic plane.

*Reference plane.* A plane 2.36 inches (60 mm)  $\pm$  0.04 inch (1 mm) above and parallel to the basic plane and which shall be located on each headform.

*Basic plane.* A plane laid out on a specific reference headform derived from the anatomic basic plane, or Reid's Baseline. (A plane at the level of the external opening of the ear and the floor of the bony rim of the eye socket.)



represent the earlier style helmet and had a webbing cradle to support the helmet on the head. (Later helmets made by this manufacturer use the polystyrene foam liner.) Helmet shells were manufactured from fibreglass reinforced resin or moulded polycarbonate, and the helmets selected represented both materials.

All the helmets were "jet style" with the shell extending down over the ears, but not surrounding the face.

Two or four examples of each type were obtained. The types were allotted reference numbers and the samples identified by a letter. Table 1 relates the reference numbers to the principal characteristics.

The masses of the helmets ranged from 0.93 kg to 1.17 kg, but five of the seven types were between 1.00 and 1.04 kg.

### 3. TEST METHOD AND EQUIPMENT

#### 3.1 Energy Absorption

To test the ability of the helmet to absorb energy and attenuate the impact, a helmeted and instrumented headform was dropped onto a rigid steel anvil. The arrangement is shown in Figure 2. The headform was of a standard shape<sup>2,3,4,5</sup> and was connected to a cross arm, shown on Figure 3, which could slide with very low friction on vertical guide wires. A spherical mounting between the cross arm and headform allowed the position of impact onto the helmet to be selected. An accelerometer was mounted at the centre of the spherical mounting with its axis vertical. The mass of the headform and spherical mounting was 4.6 kg, and with the cross arm the total mass of the assembly was 5.09 kg.

The headform was marked to show the "reference plane", described in the standards,<sup>2,3,4,5</sup> as shown on Figure 3.

Impacts were made onto a flat anvil and an anvil with a hemispherical impact surface of 48 mm radius. The anvil in use was mounted on a massive reinforced concrete reaction block with sides each approximately 600 mm long.

An adjustable release device allowed the headform to be dropped from any height up to nearly 4 m above the anvil surface.

#### 3.2 Penetration

To test the helmet's resistance to penetration, it was fitted onto a fixed headform and impacted by a sharp, conical indenter.

The headform was mounted rigidly on the reaction block of the rig and the indenter was fitted with guides which allowed it to slide freely on the vertical wires. The indenter complied with the standard requirements<sup>2,3,4,5</sup> having the shape as shown on Figure 4, a mass of 3.01 kg and an impact surface of hardened steel.

The standards<sup>2,3,4,5</sup> required that, in the specified impact the helmet should prevent the point from reaching the surface of the headform. Penetration of the point to the headform in a test was indicated by the mark left in the relatively soft headform. Two headforms were used, one complied with the current Australian<sup>5</sup> and US standards<sup>2,3,4</sup> and was made of magnesium alloy, the other was wooden and complied with earlier Australian<sup>9</sup> and European standards.<sup>1</sup> The wooden headform was used principally for preliminary testing because it could be repaired more easily than the magnesium headform.

An accelerometer was mounted on the indenter although this was not a standard requirement.

#### 3.3 Instrumentation

The primary instrumentation was a quartz piezo accelerometer in the headform, which with its associated electronics was used to display the acceleration trace on a storage oscilloscope. The trace was photographed to provide a record of the event.

The impact force on the anvil was measured in some tests by quartz force gauges positioned between the anvil and the reaction block. This system was also used to check the accelerometer by comparing the impact force and headform acceleration when a light energy absorbing plastic

foam was impacted. By adjusting the calibration factors (e.g. to  $1 \text{ km/s}^2 = 10 \text{ mm}$  and  $5 \text{ kN} = 10 \text{ mm}$ ) the traces could be superimposed.

A photo-electric timing device was used to check the impact velocity and to trigger the oscilloscope.

#### 4. TESTING PROCEDURE

The helmets were all tested at room temperature and the only "conditioning" before testing was exposure of some samples to the weather as detailed in section 4.3.

The helmets were marked with the "test line" defined in the Australian<sup>5</sup> and US<sup>4</sup> standard to assist in the choice of the impact positions.

##### 4.1 Energy Absorption Tests

In these tests the impact points were above the "test line" (relative to the wearer) but as close as possible to it. The impacts were at the side and in the frontal region, typical positions being shown on Figures 5, 6 and 7. Impacts onto the flat anvil were usually made on the left side of the helmet (Fig. 5) and those onto the hemispherical surface were on the right side (Fig. 6). Frontal impacts were usually offset from the centre line by about 60 mm (Fig. 7). This avoided impact onto a stud (usually fitted on the centre line to attach a visor) and allowed an additional impact on the other side of the centre line. As the distance between these two impact sites (120 mm) was less than the recommended minimum of one sixth of the helmet circumference<sup>2,5</sup> (typically 135 mm), the sequence of testing was arranged so that one sample of each type was tested first on a flat anvil and another sample was tested first on the hemispherical anvil. The results of tests at the second impact site were regarded as supplementary to those from the first site. A few additional impacts of other places were made for comparative purposes.

The helmets were positioned for testing by fitting to the headform so that the front edge of the helmet was approximately level with the reference line on the headform. The headform was then adjusted on its spherical mounting to give the required impact location. It was intended to impact on the test line, but this was found to be impracticable at the front of the helmet because if the helmet and headform were positioned to produce contact with the flat anvil at the test line, the contact point was offset from the centre of gravity of the headform. If the offset was too great the headform pitched violently on impact. After some trial impacts it was possible to judge a location which would give negligible pitching and this was usually between 10 and 40 mm above the test line.

Before dropping the helmet it was checked to ensure that it was in contact with the headform in the impact region and packing foam inserted opposite to the impact side if required. The assembly was then lifted to the specified height and allowed to fall and impact the anvil. After checking the impact velocity, the acceleration trace and the exterior of the helmet, the assembly was lifted again to the specified height and the helmet subjected to a second impact at the same location.

The specified drop height for impact onto the flat anvil was 1830 mm and for impact onto the hemispherical surface was 1340 mm.

##### 4.2 Penetration Tests

The helmet was mounted on the headform and the indenter dropped from a height of three metres to impact the top of the shell. After the impact the headform and helmet were examined to find out if the point had reached the headform. If the headform was damaged, the hole was filled before the next test. Usually two or more impacts were conducted on each helmet and the impact locations separated sufficiently to prevent interaction. Typical locations are shown on Figure 8.

The wooden headform was used for initial tests on most helmet types, but the metal headform was used to confirm results with each type of helmet. Those found to damage the wooden headform were tested on the metal headform at the end of the test series.

### 4.3 Exposure to the Weather

Two polycarbonate helmets (numbers 4b and 6b) were exposed to the weather, on the roof of the laboratory, for two months before commencing the tests. The period of exposure was February and March 1974. After exposure they were subjected to the test procedures of sections 4.1 and 4.2.

After completion of the tests (and a period in storage) the above helmets, together with samples of two helmets with fibreglass shells (types 3 and 5), were placed on the roof for a further period of fifteen months (November 1975 to February 1977). They were thus exposed for the greater part of two summers and the remainder of one year.

After this long exposure the helmets were subjected to the penetration tests described in section 4.2. Additional tests were carried out at the sides of helmets 4b and 6b and also on samples of these types of helmet which had been in storage. These side impacts were to allow further tests without them being too close to earlier impact sites. The wooden headform was used and was mounted on a massive support.

## 5. TEST RESULTS

### 5.1 Energy Absorption

Typical acceleration traces for the first and second impacts at the same position are shown on Figure 9. The peak acceleration during the second impact was always greater than in the first impact because of the damage to the shock absorbing foam liner caused by the first impact. Very high accelerations were evidence of "bottoming" of the padding in the second impact. (The Appendix summarises the mechanics of shock absorption in the helmet.) The peak accelerations for all helmets and test conditions are shown in Table 2 and they are seen to range from  $1 \text{ km/s}^2$  (100 g) to more than  $7 \text{ km/s}^2$  (700 g, the maximum reading on the oscilloscope scale).

Helmet type 2, with its obsolete cradle suspension gave notably higher accelerations than the other types of helmet when impacted at the side, but otherwise the variation in the results between the test conditions (i.e. order, location and impact surface) appeared greater than the variation between the helmets. To separate the effects of the "test condition" from those of the helmet, the arithmetic mean of the results from all the helmets was calculated for each test condition, and shown at the foot of each column in Table 2.

The relative severity of the tests is indicated by these results which show on average that:

1. the accelerations in the first impact were only half to three quarters of the maximum allowable value;
2. the average accelerations ( $5.1 \text{ km/s}^2$ ) in the second impact at a site near the test line at the front of the helmet, exceeded the maximum permitted value of  $4 \text{ km/s}^2$  set by most standards<sup>2,3,4,5</sup> and the limit of  $3 \text{ km/s}^2$  set by the Snell standard;<sup>10</sup>
3. the accelerations in impacts at the front were higher than those at the side;
4. the average acceleration in first impacts onto the flat anvil (1830 mm drop) were greater than those onto the hemispherical anvil (1340 mm drop).

Further insight into the standard and the helmet performance can be drawn from the proportion of the population of helmets tested, which achieved certain performance levels. Table 3 gives the numbers of tests in which the peak acceleration was less than or equal to  $3 \text{ km/s}^2$ , less than or equal to  $4 \text{ km/s}^2$  and greater than  $4 \text{ km/s}^2$ . The total number of tests in each group are also given. The results confirm the above conclusions.

For the first impact onto either surface or site the acceleration was usually less than  $3 \text{ km/s}^2$  (Table 3, Box A). The acceleration only exceeded  $4 \text{ km/s}^2$  in three tests (Table 3, Box C). Two of these were on a helmet which did not claim compliance with the test procedure and one impact was close (but not exceptionally close) to the edge of the helmet.

Very high accelerations occurred frequently in the second impact at a given site. When the helmet was impacted near to the test line, at the front, the maximum permitted acceleration was exceeded in 70% of the flat anvil tests and 56% of the hemispherical anvil tests.

Supplementary impacts were carried out with helmet types 3, 4 and 5 using a flat anvil, at a site near the top of the helmet. Helmets 3 and 4 had each produced excessive accelerations in the second impacts at the front 25-40 mm above the test line, but none of the helmets tested



near the crown produced more than  $2.4 \text{ km/s}^2$  in the first impact or  $2.7 \text{ km/s}^2$  in the second impact.

Second impacts at the side of the helmet produced excessive accelerations in 10% of the tests onto the flat surface and 28% of the tests on the spherical anvil.

The frequency of high accelerations during the impacts onto the flat anvil and onto the hemispherical anvils tended to be equalised by the different drop heights specified for the tests (1830 and 1340 mm respectively), and both anvils produced about the same number of high acceleration impacts (i.e. greater than  $4 \text{ km/s}^2$ ). The high accelerations occurred most frequently when the front of the helmet struck the flat anvil, whilst high accelerations occurred most frequently at the side when the hemispherical anvil was used. The difference in the curvature between the front and the side of both the helmet and headform is considered to be the principal reason for the difference in behaviour.

Similar tests on different samples of the same helmet type usually produced comparable results, but there were exceptions, particularly during the second impacts and some samples gave less than  $4 \text{ km/s}^2$  and others more. The number of helmet types in which all samples gave less than  $4 \text{ km/s}^2$  in a given group of similar tests is shown in Table 4. Every helmet type exceeded  $4 \text{ km/s}^2$  in at least one test.

In addition to the specification of a maximum allowable peak acceleration current standards commonly specify a limit on the duration of the acceleration at certain acceleration levels. A typical requirement in the Australian standard<sup>5</sup> is:

"the head form acceleration shall not exceed the following:

- (i) 400 g peak;
- (ii) 200 g for a cumulative duration of 3.0 ms;
- (iii) 150 g for a cumulative duration of 6.0 ms."

In ten of the tests on the flat surface the duration of the impact pulse at the  $2 \text{ km/s}^2$  level was between 2.0 and 2.4 ms, but in the remainder of the tests the duration was less than 2.0 ms. The impacts onto the hemispherical anvil produced shorter durations because of the lower impact velocity. In these tests the greatest duration at the  $2.0 \text{ km/s}^2$  level was 1.3 ms and in most tests the duration was less than 1.0 ms. The duration of the pulse at the  $1.5 \text{ km/s}^2$  level was always very much less than 6.0 ms.

The impact accelerations measured in the tests on the helmet which had been exposed to the weather for two months were not noticeably different from those with their unexposed counterparts, but one sample cracked as shown on Figure 10. Small cracks occurred in several unexposed helmets during tests, but none were as extensive as that shown on Figure 10.

## **5.2 Penetration Tests on Unexposed Helmets and Helmets Exposed to the Weather for Two Months**

Four types of helmet resisted penetration in every test. Two of these had polycarbonate shells. Two types allowed penetration in every test and one type resisted penetration in one test out of three. The results are detailed in Table 5. Only helmets 6 and 7 claimed to be able to withstand this particular test, the others having been certified to a less severe impact test requirement.

There was no noticeable difference between the performance of the two samples which had been exposed for two months and their unexposed counterparts.

The maximum acceleration of the indenter during impact was between  $1.5$  and  $2.5 \text{ km/s}^2$ , but the acceleration trace did not indicate whether the point had penetrated to the headform. Typical traces are shown on Figure 11.

## **5.3 Penetration Tests after Long Exposure to the Weather**

After fifteen months exposure the helmets were dull and discoloured. The surface coating of the fibreglass helmets, which had been cracked in the earlier tests, was peeling off and the colour of the polycarbonate shells (which was applied to the inside of the transparent shell) had faded.

When the helmets were subjected to the tests described in section 4.2 both the fibreglass helmets resisted penetration and the point did not reach the headform. Neither polycarbonate shell prevented the point from contacting the headform (Table 6).

Polycarbonate helmet No. 4 had allowed penetration before exposure, so to determine the effect of exposure, comparative tests, with a less severe impact, were carried out on the exposed



helmet and a similar helmet which had been kept in store. The impactor was allowed to fall two metres before striking the helmet and both the exposed and unexposed samples prevented the point from contacting the headform.

The impact produced a ductile depression and the appearance of the damage to the exposed and unexposed shells was similar.

Helmet No. 6 (which before the long exposure had resisted penetration and deformed in a ductile mode) cracked in two concentric circles around the impact point when tested after the long exposure. The inner crack was through the full thickness of the shell, and a disc of polycarbonate was forced into the liner leaving a hole in the shell as shown on the left hand side of Figure 12. The ductile deformation in an unexposed helmet is shown on the right hand side of Figure 12.

The disc of polycarbonate embedded in the liner is shown on Figure 13.

In four out of five tests the indenter point marked the headform. In one test no mark could be found and it is considered that the disc of polycarbonate prevented marking, but it would not have prevented a region of very high pressure on the head under the impact.

## 6. DISCUSSION OF RESULTS

The tests provided information about typical helmets and about the standard. These two aspects are considered separately although they inevitably overlap.

### 6.1 The Helmets

Most of the helmets were similar in external appearance. With only one exception polystyrene foam was used for impact energy absorption. The performance of these helmets was generally similar and they were better than the helmet with a cradle of webbing straps, particularly in side impacts.

Helmet shells were either fibreglass reinforced plastic or moulded polycarbonate. When the helmets were tested before exposure to the weather, the performance of the two types of shell was similar. The mass of most of the helmets was between 1.00 kg and 1.04 kg, so there was no apparent advantage in mass or performance with either fibreglass or polycarbonate. (Retail costs were similar too, but undoubtedly manufacturing costs would differ.) When tested after 18 months exposure to the weather, one of the polycarbonate shells showed severe degradation in resistance to penetration. A polycarbonate shell from a different maker and two fibreglass shells did not show comparable degradation in performance after similar exposure.

Most of the helmets limited the impact acceleration in the first impacts to less than 3 km/s<sup>2</sup> when tested at the front or the side. Second impacts at the side were usually limited to less than 4 km/s<sup>2</sup> but most of the second impacts at the front of the helmet near (10–40 mm above) the test line, and thus above the reference plane, resulted in accelerations in excess of 4 km/s<sup>2</sup>. Most of the helmets claimed compliance with Z90.1 of 1966 or 1971 which state:

“9.2.1 Any peak acceleration of the test headform with any of the four pre-conditioned protective headgear, exceeding 400 Gs shall be cause for failure.”

Perhaps compliance tests had been carried out with impacts further from the edge; this is allowable in the standard, but may not demonstrate performance over “The entire area . . . above the reference plane.”

Impacts near the edge at the front are particularly severe because:

1. the radius of the headform is a minimum and this limits the area which is in compression;
2. the edge of the helmet further truncates the crushing area;
3. the liner of some helmets is thinner near the edge to accommodate the headband or comfort padding.

The difficulty is further compounded by the requirement for a double impact. (Comments on the effects of crushing area and liner thickness are given in the Appendix.)

Some helmets were successful in limiting the second impact at the front to less than 4 m/s<sup>2</sup>, showing that this can be achieved.

Consideration of the accident data, and the definition of the “extent of protection”, shows that satisfactory performance at the front of the helmet is required in service, and is implied by the standard. It is considered that helmet performance in this region should generally be improved.

About half the helmets were able to prevent penetration of the indenter to the headform after impact from three meters. This group of helmets included some which had been certified to a lower standard,<sup>3</sup> and they were not heavier than the group which did not prevent penetration to the headform.

## 6.2 The Inferences of the Results in Relation to the Standards

One of the most important sections of any helmet standard is definition of the extent of protection. Ideally the helmet would provide protection when struck anywhere on the shell. Practically, there must be some allowance for reduced performance at the extreme edges and a "test line", at a specific distance from the edge, indicates a practical limit to the area required to give the specified performance.

Testing near the edge presents practical difficulties because the helmet tends to pitch on impact. The subjective procedure used to select locations which were close to the test line, but which did not cause excessive pitch cannot be written into a standard, nevertheless it is considered that the standard should demand proof of satisfactory performance in this region.

The permitted maximum impact acceleration of  $4 \text{ km/s}^2$  is considered a practical value for certification purposes. The limit could be reduced to  $3 \text{ km/s}^2$  for the first impacts and in theory the design for lower transmitted acceleration should result in a safer helmet, however in practice the requirement for two impacts at the same place, and the limit of  $4 \text{ km/s}^2$  on both impacts, ensures that the acceleration in the first impact is less than  $4 \text{ km/s}^2$ .

As noted in section 5.1 some standards impose limits on the duration of the pulses at certain acceleration levels. It is generally agreed that the probability of injury depends both on the magnitude and duration of the acceleration pulse. In the consideration of human tolerance to impact this is understandable because the potential for injury is clearly influenced by the velocity of the impact, and this is the integral of acceleration with time. In the context of helmet testing the impact velocity is set by the drop height, and as rebound, which can also affect the duration of the pulse, is likely to be small the acceleration would appear to be the most important factor. It is considered that the limits on duration are redundant.

The penetration test with an indenter dropped through three metres is a very severe test either in comparison with earlier standards or with the drop onto the flat and hemispherical surfaces. The tests, however, indicate that it is practicable with currently available materials and it does not impose an undue weight penalty.

Durability is an important feature of safety equipment. Tests are provided in the standards to determine the effects of heat, cold and water saturation, but the many other influences are usually referred to only by a descriptive clause<sup>2,3,5</sup> such as

*"Materials. Materials shall be of durable quality, such that their characteristics will not undergo appreciable alteration under the influence of ageing or the circumstances of use to which the helmet is normally subjected, i.e. exposure to sunlight, rain, cold, dust, vibration, contact with skin, perspiration or products commonly applied to the skin or hair."*

Helmet 6 did not fulfil the objectives expressed in the clause and greater attention should be given to ensuring the use of suitable materials and the use of degradation inhibitors, where necessary. The standard should give more definitive instructions.

## 7. CONCLUSIONS

When typical helmets were tested according to the current US and Australian standard the tests showed that

1. Most helmets cushioned the first impact and limited the peak acceleration to less than 75% of the permitted value.
2. A second impact at the same site resulted in a higher peak acceleration and impacts near the edge at the front of the helmet usually resulted in an acceleration in excess of the permitted value. Hence to comply with the standard, protection should be improved in this region.
3. About half the helmets prevented penetration to the headform of the pointed indenter after it had fallen through three metres.

4. The performance of new helmets with fibreglass and polycarbonate shells was similar. The masses of the helmets were also similar so when new neither shell material showed a marked advantage with regard to performance.
5. Two helmets with fibreglass shells and two with polycarbonate shells were tested for penetration resistance after having been exposed to the sun and weather for about 17 months. After exposure the appearance of the helmets was poor and colours had faded but the two fibreglass helmets did not show a measurable reduction in performance. One of the polycarbonate helmets retained its resistance to penetration and the shell remained ductile after exposure. This helmet had lower resistance to penetration than the other three types when tested before exposure but withstood impacts from two metres before and after exposure. The remaining polycarbonate helmet suffered serious degradation in performance and the effect of impact on the shell changed from ductile deflection to brittle fracture.
6. The results generally endorse the test criterion of the standards, in particular—
  - (a) The limit of  $4 \text{ km/s}^2$  (400 g) is considered satisfactory in conjunction with the paired impacts on each test site.
  - (b) The three metre drop of the indenter in the penetration test is practicable and should not result in an undue weight penalty even though it is much more severe than earlier tests.
7. The results did indicate that the standard should be more detailed in two aspects—
  - (a) Tests should be required to show the performance in impacts at the front near the edge (or test line).
  - (b) Durability requirements should be expressed more forceably.



## **APPENDIX**

### **The Mechanics of Shock Absorption**

During impact the headform is decelerated by a force transmitted from the anvil by the helmet. Crushing of the foam plastic liner and deflection of the shell control the deceleration and provide the required stopping distance. "Rigid" foams (and some "semi-rigid" foams) are effective because they resist compression by the strength of their cell walls, but can be crushed through a large proportion of their thickness (70-90%) before the cells are flattened. The crushing stress (resistance) usually increases with compression as the cell walls are broken but increases greatly when they are flattened—this is known as "bottoming". The crushing stress should be such that with the area of foam under compression, the force as the cells are crushed does not produce more than the specified impact acceleration, but on the other hand the force must be large enough to decelerate the head completely before the foam "bottoms". Rigid foams do not recover after they have been crushed so if a second impact is to be applied, the material must not be fully crushed in the first impact.

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**TABLE 1**  
**The Helmets**

Type ref.	Standard claimed	Shell material	Shock absorber	Number of Samples	Mass (kg)
1	Z90.1-1966 <sup>3</sup>	fibreglass	foam	2	1.00
2	E43-1968 <sup>9</sup>	fibreglass	cradle	2	1.04
3	Z90.1-1966 <sup>3</sup>	fibreglass	foam	4	1.02
4	Z90.1-1966 <sup>3</sup>	polycarbonate	foam	4	1.02
5	Z90.1-1966 <sup>3</sup>	fibreglass	foam	4	1.17
6	Z90.1-1971 <sup>2</sup>	polycarbonate	foam	4	1.04
7	Z90.1-1971 <sup>2</sup>	polycarbonate	foam	2	0.93

Note: Superscripts by standards correspond with the references.

**TABLE 2**  
**Accelerations in Energy Absorption Tests—km/s<sup>2</sup>**

Helmet type	Sample	Impact onto flat anvil				Impact onto hemispherical anvil			
		Front		Side		Front		Side	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd
1	a	2.0	2.4	1.9	2.1	—	—	0.8	3.1
1	c	5.3 <sup>1</sup>	5.8	1.9	2.2	1.6	7.0+	1.2	6.0+
2	a	4.0	7.0	2.7	5.3	3.0	3.5	4.7	6.0+
2	c	5.0	6.4	3.0	6.0+	4.0	6.0+	3.8	4.3
3	a	3.6	7.0	2.0	2.3	2.2	3.9	1.0	2.9
3	b	2.9	6.7	2.5	—	2.2	6.0	1.2	1.6
3	c	2.6	6.0	1.7	2.8	3.4	6.4	1.4	1.6
3	d	2.2	—	2.0	2.6	1.1	3.7	1.4	1.7
4	a	3.4	6.5	2.4	3.0	—	—	1.2	1.6
4	b	2.9	7.0	2.4	2.7	—	—	1.2	1.6
4	c	—	—	2.7	3.2	1.5	4.3	1.3	—
4	d	3.7	—	2.5	3.0	1.3	5.7	1.4	2.2
5	a	2.1	3.2	2.0	2.4	—	—	1.0	—
5	b	2.0	2.5	1.9	2.5	1.0	1.5	1.1	1.6
5	c	—	—	2.1	2.5	1.1	7.0+	1.1	4.2
5	d	2.1	2.6	2.2	2.6	—	6.0+	1.3	6.0
6	a	2.2	4.2	2.8	3.5	1.1	2.8	1.4	1.8
6	b	3.7	5.6	2.8	2.9	1.5	5.3	1.4	1.8
6	c	2.2	4.3	—	3.2	1.2	1.4	1.2	1.0
6	d	1.6 <sup>2</sup>	2.0 <sup>2</sup>	—	—	—	—	—	—
7	a	2.0	6.6	3.0	—	—	—	—	—
7	c	2.2	3.8	2.4	2.9	1.25	3.7	1.4	4.0
Mean		3.0	5.1	2.3	3.0	1.8	4.6	1.5	2.9
Std. deviation		1.0	1.7	0.4	1.0	1.0	1.8	1.0	1.7

Notes—1. 20 mm above test line.

2. An extra layer of foam padding was inserted for these tests. (results not included in Tables 3 and 4)

**TABLE 3**  
**Number of Tests Producing Impact Acceleration Peaks in the Given Ranges**

Impact	Impact acceleration peak						Total impacts	
	Up to 3 km/s²		Up to 4 km/s²		Over 4 km/s²			
	Flat anvil	Spher-ical anvil	Flat anvil	Spher-ical anvil	Flat anvil	Spher-ical anvil	Flat anvil	Spher-ical anvil
Box reference	A		B		C			
First at front	12	13	17	15	2	0	19	15
First at side	20	18	20	19	0	1	20	20
Box reference	D		E		F			
Second at front	3	3	5	7	12	9	17	16
Second at side	14	11	17	13	2	5	19	18

**TABLE 4**  
**Number of Helmet Types Producing Acceleration Peaks up to, but not Greater than, 4 km/s<sup>2</sup>**  
**(7 helmet types tested)**

Impact	Flat anvil	Spherical anvil
First at front	5	7
First at side	7	6
Second at front	1	1
Second at side	6	4



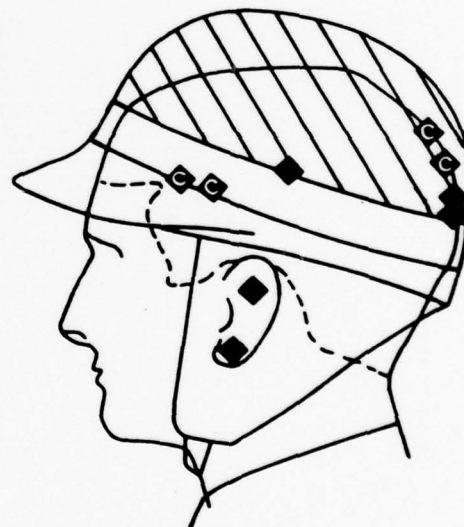
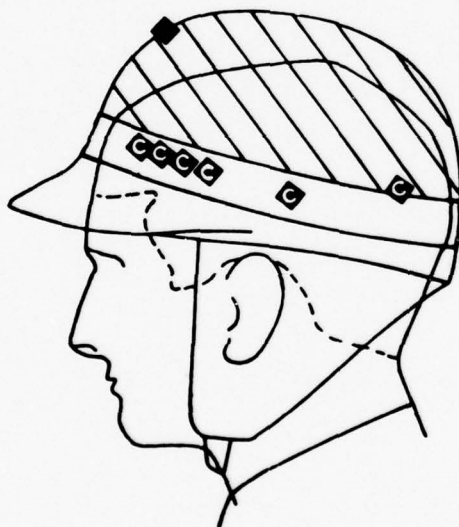
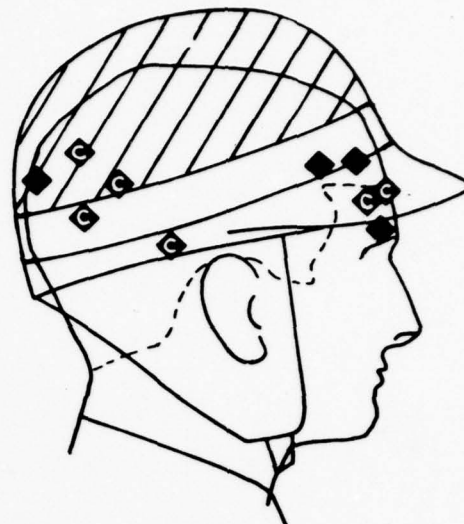
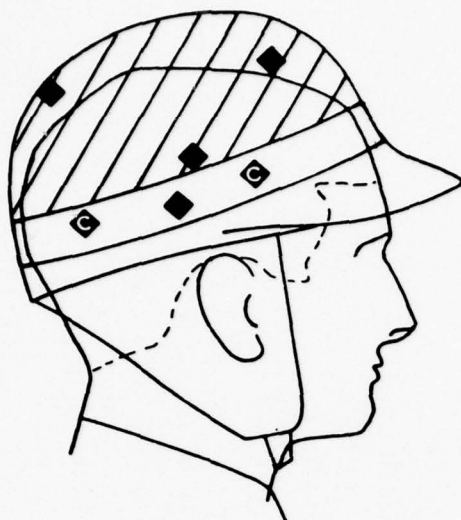
**TABLE 5**  
**Results of Penetration Tests—Before Long Exposure**  
 (3 metre drop)

Helmet type Shell material	1 G	2 G	3 G	4 P	5 G	6 P	7 P
Number of tests	3	3	3	3	3	3	3
Number of times penetrated	2	3	0	3	0	0	0

Notes: G—fibreglass, P—polycarbonate

**TABLE 6**  
**Results of Penetration Tests After 15–17 Months Exposure**  
 (3 metre drop)

Helmet type	1	2	3	4	5	6	7
Number of tests	—	—	3	3	3	5	—
Number of times penetrated	—	—	0	3	0	4	—



Cases where a helmet was worn, showing the position of impacts in relation to the shell of the helmet and the protective padding. The cross-hatched area indicates the extent of the padding. 'C' indicates an impact causing concussion.

Cases where helmets were not worn, showing the position of the impacts in relation to the area covered by the shell of the helmet and its protective padding. The cross-hatched area indicates the extent of the protective padding. 'C' indicates an impact causing concussion.

FIG. 1 IMPACT LOCATIONS FROM A SURVEY OF TRAFFIC ACCIDENTS (Reproduced from Ref. 8)

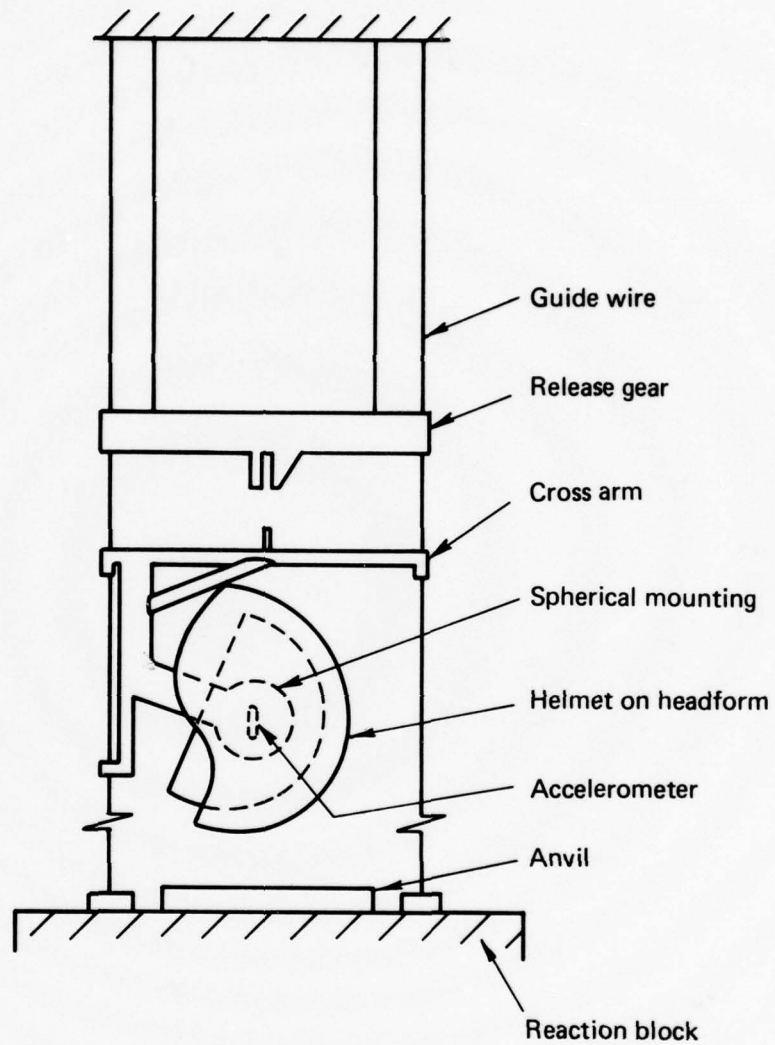


FIG. 2 DIAGRAMMATIC ARRANGEMENT OF TEST RIG.

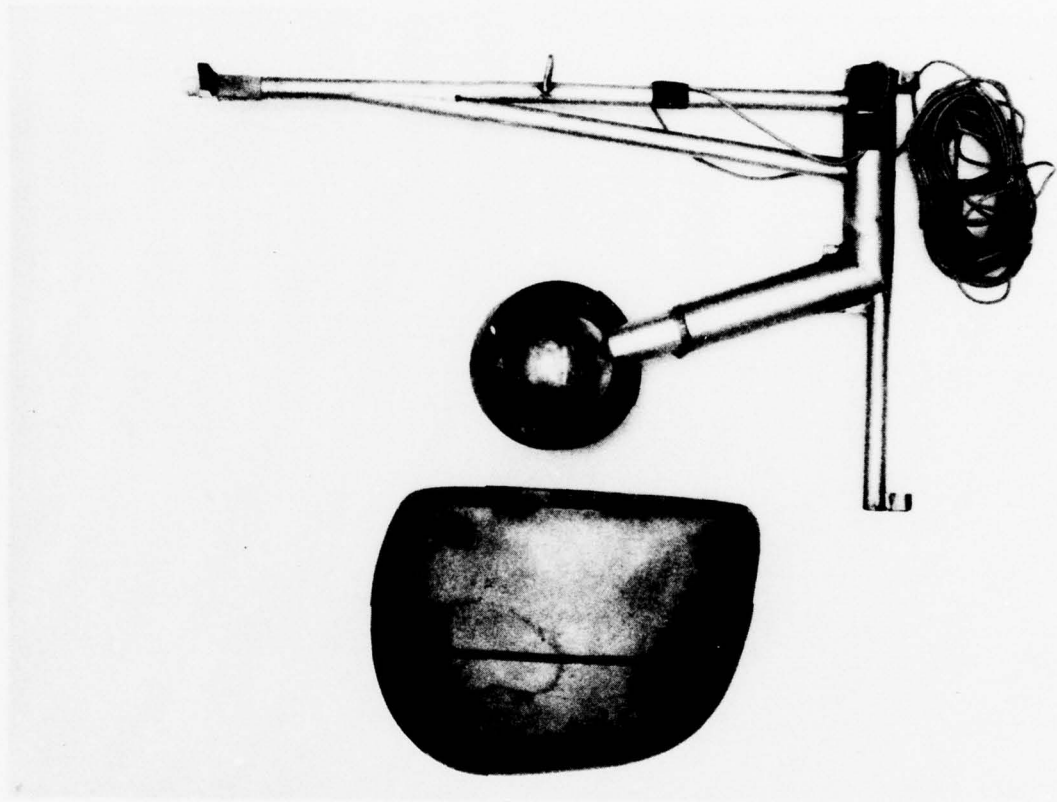


FIG. 3 TEST HEADFORM WITH 'REFERENCE LINE' AND CROSS ARM WITH SPHERICAL MOUNTING

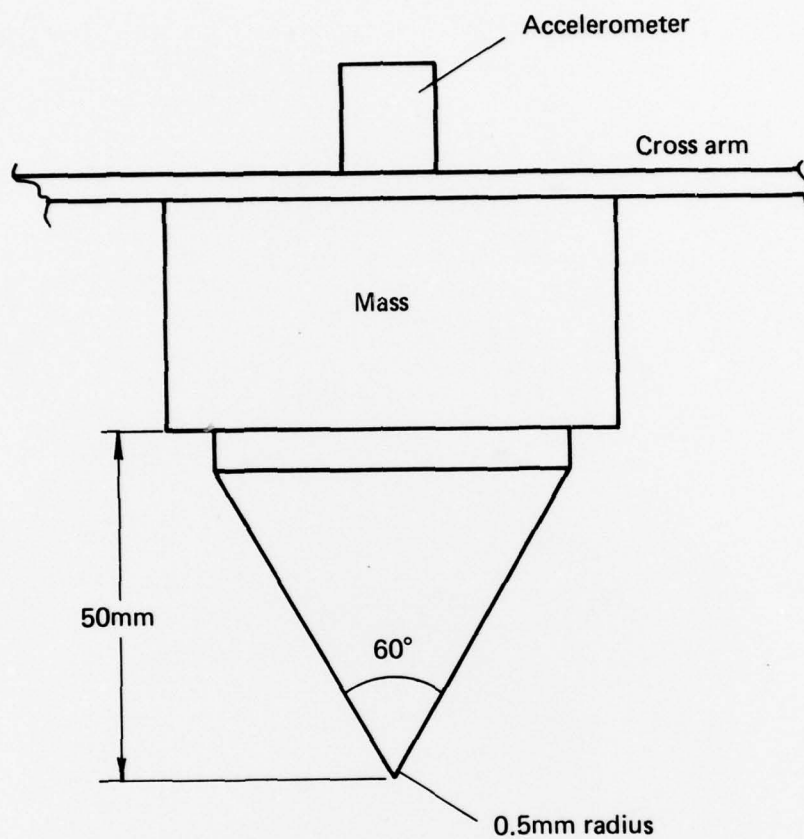


FIG. 4 INDENTER FOR PENETRATION TESTS



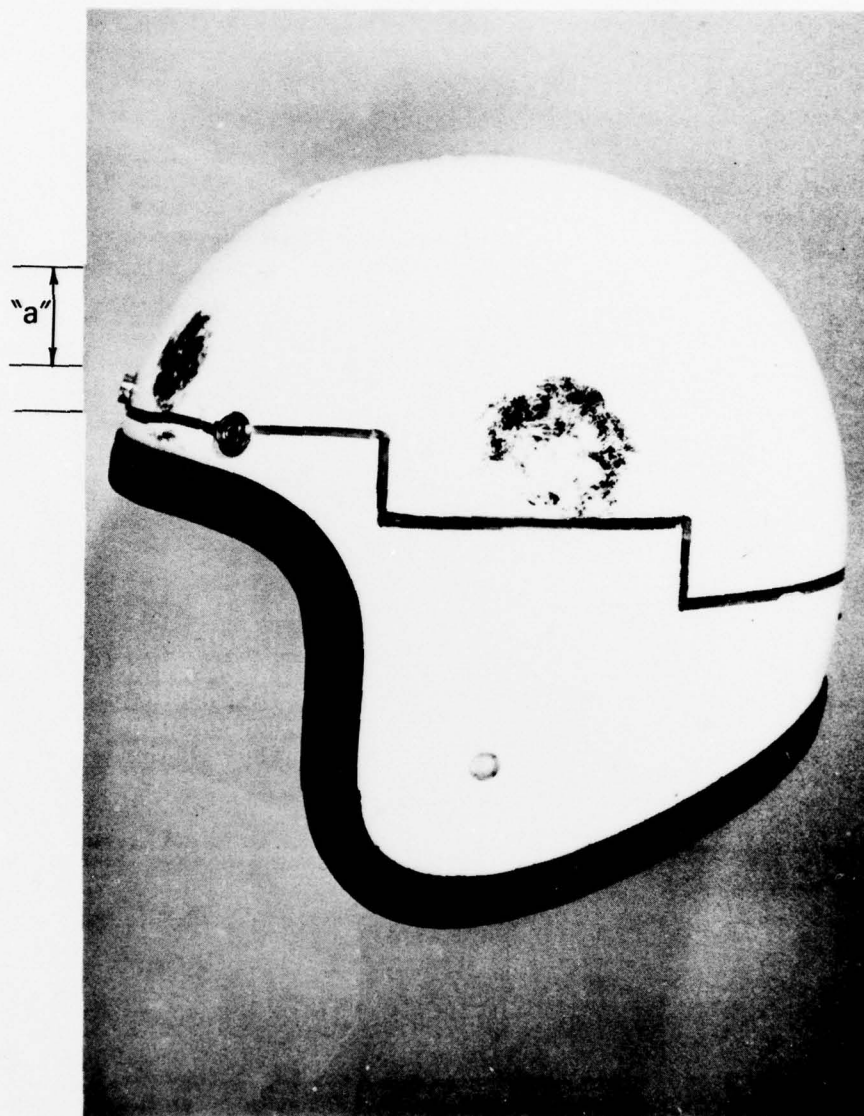


FIG. 5 LEFT SIDE OF HELMET SHOWING 'TEST LINE' AND LOCATION OF IMPACTS ON TO THE FLAT ANVIL AS MARKED BY CARBON PAPER FACE UP ON THE ANVIL (The centres of the frontal impacts were mostly between 10 mm and 40 mm above test line as indicated by the zone 'a'.)

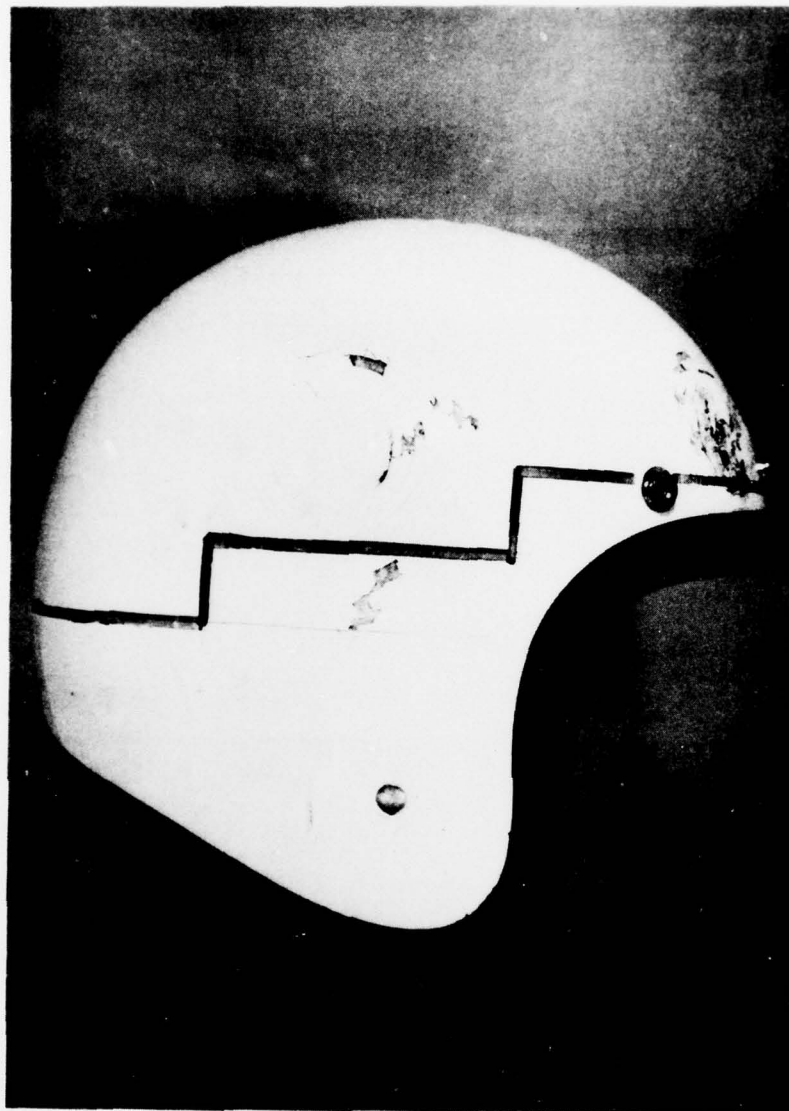


FIG. 6 RIGHT SIDE OF HELMET SHOWING TEST LINE AND CRACKS  
FROM IMPACTS ON TO THE SPHERICAL ANVIL



FIG. 7 FRONT OF HELMET SHOWING LOCATION OF FRONTAL IMPACTS



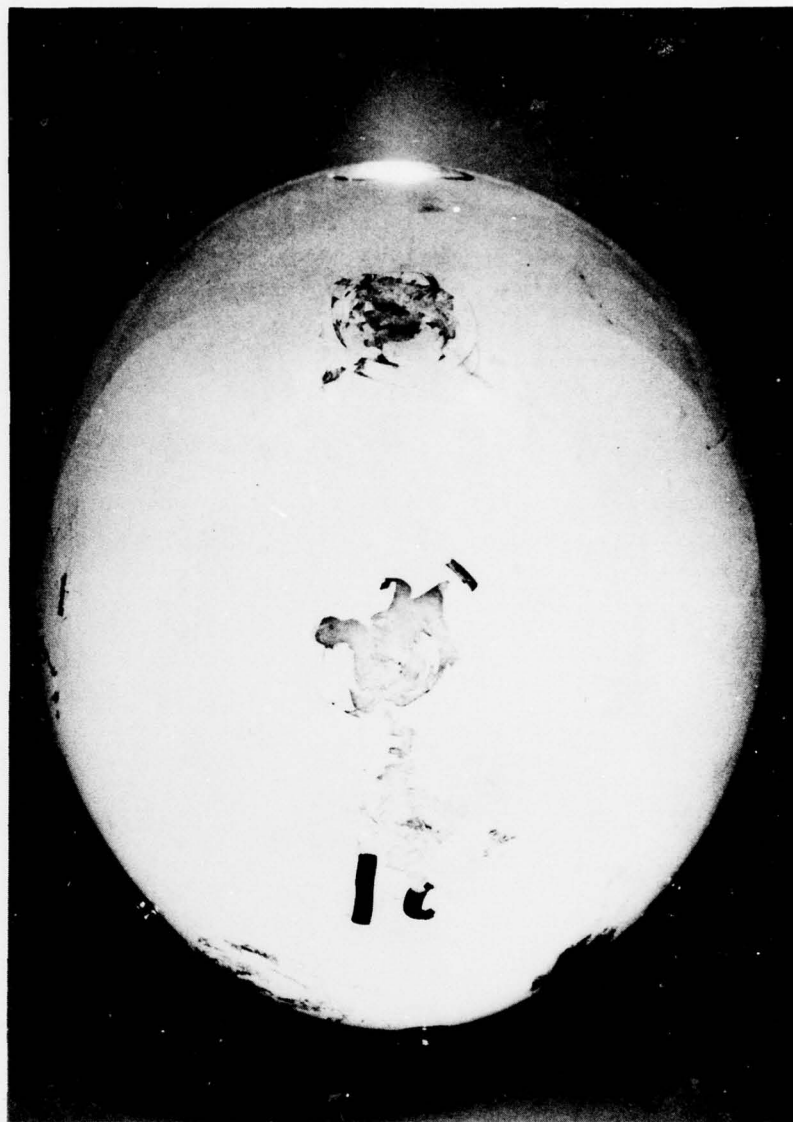


FIG. 8 TOP OF HELMET SHOWING TYPICAL LOCATIONS OF PENETRATION TEST IMPACTS

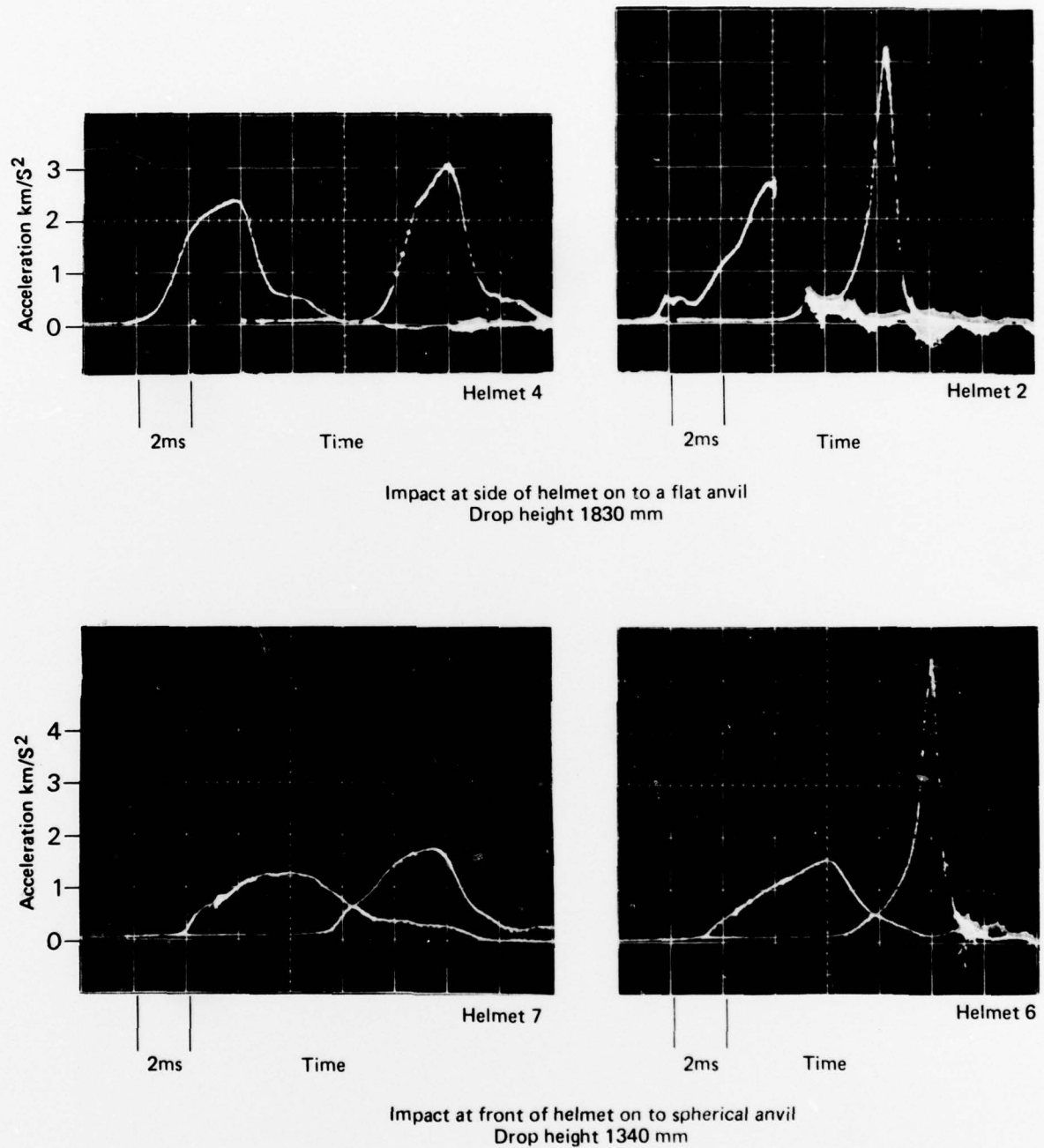


FIG. 9 TYPICAL ACCELERATION TRACES FOR THE FIRST AND SECOND IMPACTS AT THE SAME POINT ON THE HELMET (The oscillograph was set to position the trace for the second impact to the right of the trace from the first impact)



FIG. 10 CRACK IN HELMET NO. 6 IN SIDE IMPACT ON A FLAT SURFACE  
AFTER TWO MONTHS EXPOSURE TO THE WEATHER

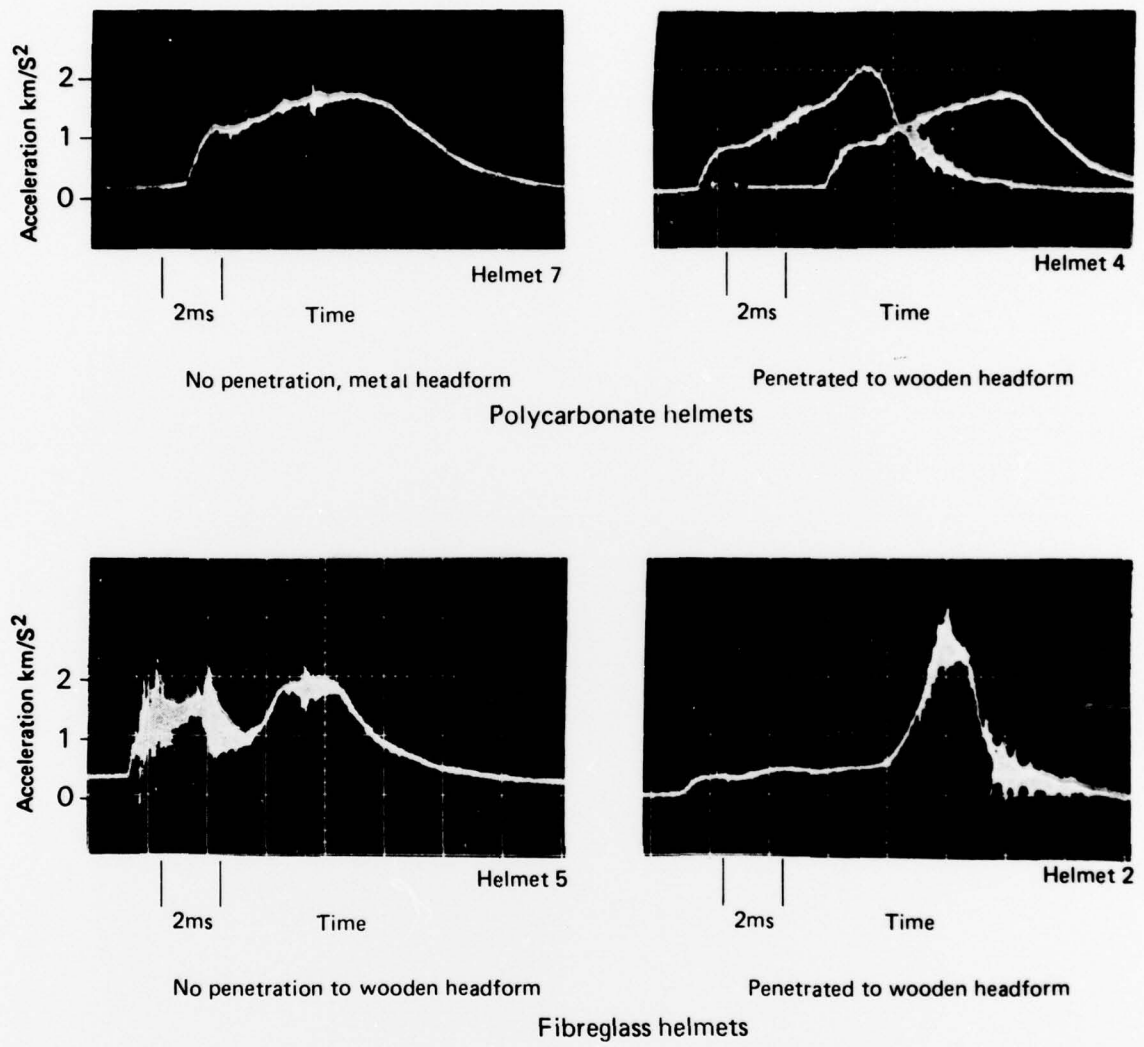


FIG. 11 TYPICAL ACCELERATION TRACES FROM THE PENETRATION TESTS



FIG. 12 THE EFFECT OF WEATHERING ON RESISTANCE TO PENETRATION ON HELMETS NO. 6b and 6a. The two upper left indentations on the left hand helmet and all those on the right hand helmet resulted from impacts before prolonged exposure to the weather. The four holes with concentric tracks seen in the left hand helmet resulted from impact tests after 17 months exposure on the roof of the laboratory.



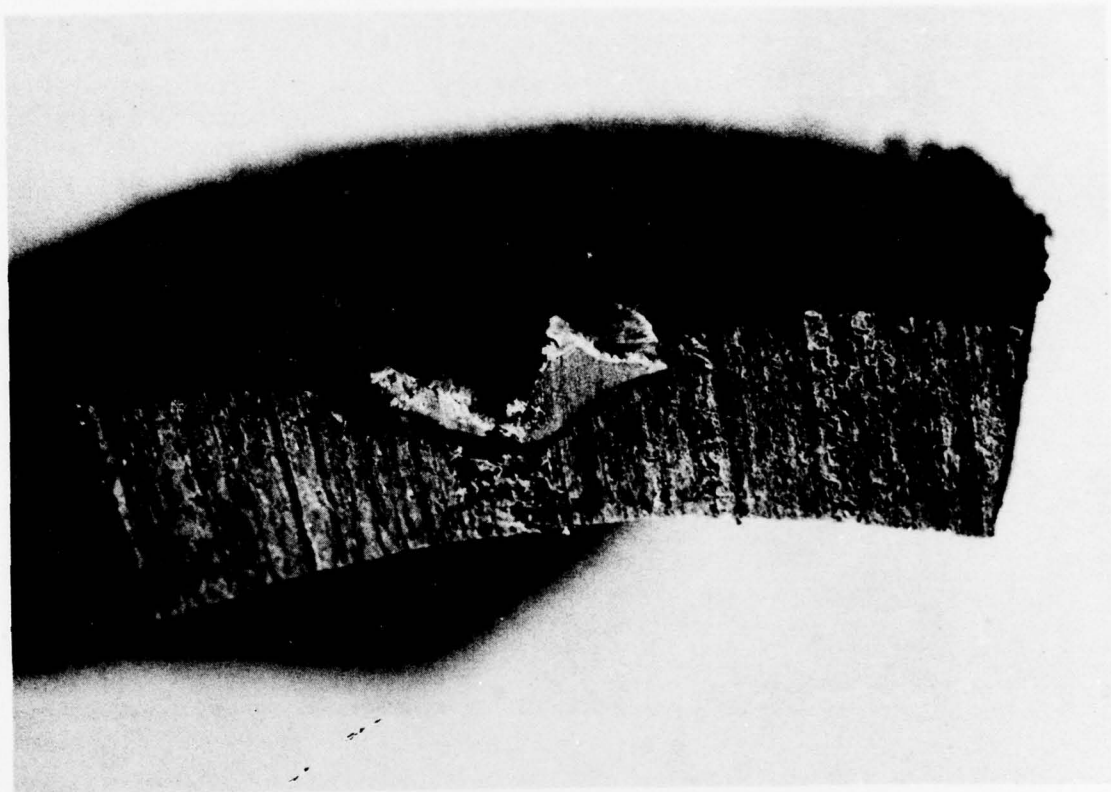


FIG. 13 SECTION OF LINER FROM THE HELMET SHOWN IN FIG. 11, SHOWING THE CENTRAL 'DISC' OF SHELL MATERIAL PRESSED INTO THE FOAM PLASTIC LINER. (In one test this 'disc' prevented the contact and marking of the head form by the indenter)

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Security classification of this page: Unclassified

<p>1. Document Numbers</p> <p>(a) AR Number: AR-001-263</p> <p>(b) Document Series and Number: Structures-Note-445</p> <p>(c) Report Number: ARL-Struc.-Note-445</p>	<p>2. Security Classification</p> <p>(a) Complete document: Unclassified</p> <p>(b) Title in isolation: Unclassified</p> <p>(c) Summary in isolation: Unclassified</p>															
<p>3. Title: IMPACT TESTS ON CRASH HELMETS FOR MOTOR CYCLISTS</p>																
<p>4. Personal Author(s): N. D. Hearn S. R. Sarraillhe</p>	<p>5. Document Date: April, 1978</p>															
<p>6. Type of Report and Period Covered:</p>																
<p>7. Corporate Author(s): Aeronautical Research Laboratories,</p>	<p>8. Reference Numbers</p> <p>(a) Task:</p>															
<p>9. Cost Code: 26 5071</p>	<p>(b) Sponsoring Agency:</p>															
<p>10. Imprint Aeronautical Research Laboratories, Melbourne</p>	<p>11. Computer Program(s) (Title(s) and language(s)):</p>															
<p>12. Release Limitations (of the document): Approved for public release</p>																
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<p>13. Announcement Limitations (of the information on this page): No limitation</p>																
<p>14. Descriptors:</p> <p>Helmets                      Headgear</p> <p>Protective clothing       Penetration tests</p> <p>Impact tests                Glass fibres</p> <p>                                 Polycarbonates</p>	<p>15. Cosati Codes:</p> <p>0617</p> <p>1402</p>															

16.

### ABSTRACT

*Seven types of crash helmet were subjected to a series of impact tests to the current Australian and US standards. Impact accelerations were usually less than 75% of the maximum permitted value but second impacts near the edge of the front usually resulted in excessive accelerations.*

*Four types were exposed to the weather for 15-17 months. Two had fibreglass shells, two had polycarbonate shells and one of the latter suffered significant degradation in its resistance to penetration.*

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